THE EFFECT OF VEGETATIVE EVAPORATION ON THE RATE OF SEASONAL TEMPERATURE CHANGES.[1]

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SYNOPSIS.

Data are given showing that the evaporation of water transpired from vegetation causes a definite local cooling. An attempt to show that vegetative evaporation affects large areas is made by comparing spring average daily temperature curves of continental stations in arid and humid regions. Four figures are given showing a flattening in such curves for the stations in humid regions with less flattening, or none at all, for the stations in arid regions. It is pointed out that several factors, among them the control of weather by HIGHS and LOWS, tend to obscure departures from a smooth curve caused by vegetative evaporation but the evidence seems to indicate that vegetative evaporation has an appreciable effect.

The effect of temperature on vegetal growth is well known but that vegetal growth, in turn, affects air temperatures has not received much attention. When one considers the immense quantities of water transpired from succulent plant growth and the amount of heat rendered latent by its evaporation he can not but be impressed by the thought that this phenomenon must have some appreciable effect on air temperatures. Quantitative values of the cooling effect due to vegetative evaporation over large areas are not easily determinable, for they are obscured by varying rainfall, soil moisture, and exposure to sunshine; by atmospheric circulation in HIGHS and LOWS; by variability of the seasons; and by all the effects of radiation and absorption.

It was found by Darwin[2] that the difference in temperature between two leaves—one freely transpiring and the other not at all—may amount to 1.5° C. Were it not for the fact that vegetation is a much better absorber of radiation than air we would expect to find, during the growing season, that all succulent portions of plants have temperatures appreciably lower than that of the air. It is to be expected, however, as has been confirmed by quantitative measurements by Seeley[3] and others that in sunshine the heating of plants, with moderate water requirements, due to the absorptive power of vegetation predominates over the cooling due to evaporation, and that parts of such plants exposed to direct insolation have temperatures considerably higher than that of the surrounding air—though obviously not as high as they would have were there no evaporation. From experiments conducted with sunflower plants it was computed by Brown[4] that if the transpiration loss of water were suddenly stopped during bright sunshine the temperature of the leaves would rise, for a short time, at the rate of 12° C. per minute. Briggs and Shantz[5] have found by careful and accurate measurements that the leaves of plants with high water requirements often have temperatures lower than the surrounding air even when exposed to direct radiation in clear, dry air. The amount of heat used by evaporation at time of maximum is for many plants well over one half of the total heat received from all sources.[4,6] "In some of the small grains the energy dissipated through transpiration is twice the amount received directly from the sun."[6] It should be borne in mind, too, that parts of most plants are shaded during a considerable portion of the day.

The loss of heat varies, of course, with the amount of water evaporated. The quantity of water transpired by many different plants is given in nearly all good textbooks on Botany or Plant Physiology. The daily transpiration of 22 of our common crops has been determined by Briggs and Shantz.[6] Accurate measurements of the amount of transpiration over large forested areas have never been made, though the estimates of many independent observers show very close agreement.[7,8] The evaporation from a single, small, isolated tree in the course of a day amounts, in many instances, to well over 36 kg. of water.[9] The heat required to produce this evaporation exceeds 20 million gram-calories. If this heat consumption were applied to cooling air it would reduce by 1° C. the temperature of 80,000 cubic meters, equal to a column 1 km. high over an area of 80 square meters. One could not take this as a basis and by counting the number of trees in a unit forest area find the total cooling effect for such an area because under the same condition of soil moisture a tree in the forest will not evaporate as much as an isolated tree in the open. A wind that blows past such a transpiring tree, or other surface, has just come from, and immediately passes on to, other transpiring areas (except at the border between vegetated and nonvegetated areas) so that its humidity is higher and temperature lower than the normal for air over nonvegetated land at the particular locality. With vegetal covers of widely varying water requirements winds lessen marked local cooling over the more rapidly transpiring areas and cause a mixing of the air, resulting in more uniform temperatures over different areas.

The question of the effect of vegetative evaporation on air temperature has been discussed by Ney,[10] who suspects that it has an appreciable effect and gives some theoretical values that are rather startling though computation shows that they hold for about all moist regions of the temperate zones and are much smaller than may be found over large sections of the eastern part of the United States that are well covered with vegetation. He computed that they average heat loss by evaporation in one day during the growing season from an area of 10,000 square meters (2.47 acres, 1 hectare) covered by some typical plant growths would reduce by 1° C. the following volumes of air:

	Cubic meters.
Pine forest	12,000,000
Grain (wheat, rye, etc.)	35,000,000
Meadow (timothy, clovers, etc.)	81,000,000

At the time of maximum transpiration these values are greatly exceeded.

Of the three general classes indicated above, grasses and clovers are the most potent dessicators of the soil and pine forests the least. Most broad-leaved trees, however, transpire several times as much water as conifers.[11]

The evaporation from the ground itself is, of course, considerable and increases with increase of temperature so long as the soil is very moist. Ney computed that the evaporation from the vegetative surfaces for the time and conditions mentioned above averages, for western Germany, 4 grams of water more per day over 1 square meter

[1] The author is indebted to Dr. W. J. Humphreys for assistance in the selection of this problem for investigation and for many helpful criticisms.
[2] Francis Darwin. *Bot. Gaz.*, Feb., 1904, vol. 37, No. 1, p. 81.
[3] D. A. Seeley. MO. WEATHER REV., July, 1917, p. 354; and *Mich. Acad. Sci.* 19th Rept., 1917.
[4] H. T. Brown. Fixation of Carbon by Plants, *Nature*, Sept. 14, 1899.
[5] From results as yet unpublished, but authority to quote given.
[6] L. J. Briggs and H. L. Shantz. *Jour. Agri. Res.*, vol. 7, No. 4, 1916.
[7] Raphael Zon. Forests and Humidity, *Sci.*, p. 63, July 18, 1913.
[8] Ebermayer. Die physikalischen Einwirkungen des Waldes, etc., Aschaffenburg, 1873, S. 202.
[9] Vegetable Physiology; Green, p. 91; Plant Physiology; Duggar, p. 87, etc.
[10] C. E. Ney. *Met. Zeit.*, Dec., 1885, p. 445.
[11] Alfred Burgerstein. Die Transpiration der Pflanzen, Jena, 1904, p. 64.

than from the same land, moist, but with no vegetal covering. The normal rainfall for most of the stations studied in the following discussion, except where mentioned, varies but slightly during the time involved.

The growth of vegetation affects the temperature by three processes besides that directly due to evaporation: (*a*) Plant respiration similar to that of animals (most pronounced in the germination of seeds and in flowering)—giving off carbon dioxide and absorbing oxygen—an exothermic reaction; (*b*) the use of energy in the raising of water from roots to higher portions, and (*c*) the formation of carbohydrates, an endothermic reaction. The heat used by *c* is merely stored, becoming available later when the vegetal growth is used as fuel. The cooling due to *c* which is continuous during the growing season, but most pronounced during spring and early summer, greatly exceeds the heating due to *a* and may amount to 2 per cent [4] of that due to evaporation. The heat used in *b* amounts to only 0.0004 per cent, roughly, of that used in evaporation. Of these three factors *c* is the only one that produced an appreciable effect but it, too, is small in comparison with the effect due to evaporation which, therefore, alone will be considered in this discussion.

Vegetative evaporation starts from a relatively small amount some time before the average date of the last killing frost and approaches a maximum when the leaves of most trees have become full-sized and grasses and grains have made substantial growth, or within 30 days, say, from that date. The time after the last killing frost before vegetative evaporation reaches a maximum varies with the latitude. In the northern portion of the United States, except in mountainous regions, where the vegetative period [12] nearly coincides with the frostless period, the maximum is reached near the end of the 30-day period, while in the southern part of the United States where the vegetative period greatly exceeds the frostless period the maximum is apt to be reached nearer the beginning of the frostless period.

It is frequently noted that in passing abruptly on a hot, comparatively calm summer afternoon from a field of bare soil to land that is covered by succulent grass or clover a perceptible difference in temperature is encountered (in addition to that found on entering a forest). This is especially striking if the vegetal cover happens to be alfalfa or other plant with high water requirements.

There is plenty of evidence, therefore, that vegetative evaporation has some appreciable effect on air temperatures though whether it is sufficient to show through the other factors in control of temperature is not so obvious. We would expect, if the evaporation effect is sufficient, that it would tend to produce a flattening in the curve of average daily temperature, during the period abovementioned, or that the temperature curve for an arid region would be steeper at this time than the curve for a corresponding humid region. In this connection one would have to consider the difference in slope due to any difference in the annual range of temperature between the arid and humid regions. Of course, vegetative evaporation lasts all season but, being continuous after once started, its effect on the slope of the temperature curve is not very noticeable except near the beginning and possibly at the time of defoliation, though in the autumn it decreases so gradually, as a rule, that its effect on the slope of the curve of average daily temperature is small compared with the effect produced in the spring.

To obtain some qualitative indications of this evaporation effect the average daily temperatures of stations in continental arid and humid regions having the same frostless period were compared. Figure 1 shows the somewhat smoothed curves of the average daily temperatures of Columbia, Mo., and Pueblo, Colo., from April 12 to May 31.[13] (The average date of the last killing frost is about April 21 for Columbia and a little later for Pueblo.) Both curves show a flattening about the last of April, while Columbia only has a pronounced change in slope. The flattening at Columbia persists until May 7, while the temperature at Pueblo rises rapidly from May 1. A large part of the curious cool period about the last of April at both stations is undoubtedly due to the effects of HIGHS and LOWS, which a very long record probably would lessen. The data upon which the curves are based are for the 30-year period ended 1918. Most of the marked irregularities for all stations studied are parallel and occur a day or so earlier in the western (arid) than in the eastern (humid) regions, which is to be expected if the irregularities are due to the movements of certain particularly effective HIGHS and LOWS. Pueblo, Colo., has considerable rainfall, and consequently some vegetal growth during the time covered by the curves and it is natural to suppose that the difference in the slope of the two curves is not as great as it would be for two stations having a greater contrast in rainfall and vegetation.

Figure 1 shows also the smoothed daily temperature curves for Birmingham, Ala. (humid), and El Paso, Tex. (arid), from March 16 to April 28, based on 23 and 31 years' record, respectively. The average date of the last killing frost for both stations is about March 29. The flattening in the Birmingham curve from March 29 until April 8 is very pronounced while El Paso shows an almost steady rise. The slope of the curve for Birmingham from April 9 to April 17 is steeper than for El Paso for the same period, which would be anticipated since the normal rise for Birmingham has been checked for so long a time; also the normal rainfall for Birmingham decreases quite rapidly from the latter part of March. This long continued flattening and subsequent recovery, similar to that found at several southern stations, somewhat obscures, with only moderate smoothing, the change in general slope of the curves that is so pronounced for all more northern stations whose records were studied.

Figure 1 shows further the mean daily temperature for Springfield, Ill., and El Paso, Tex., from March 1 to July 1. The rate of rise for Springfield is quite uniform until the last of April, when an abrupt change in slope, shown by the dotted line, occurs. No such change occurs in the curve for El Paso; in fact, the slope increases slightly after the curious cool spell of April 28 to May 3. The original curve for Springfield shows a flattening during the first few days of May, but as it occurs immediately after the cool spell above mentioned it is somewhat obscured. The change in slope at most of the other stations (see Table 1) in humid regions that were studied is similar and about of the same order of magnitude as that shown by Springfield.

As further evidence that the change in slope, however modified by other factors, is largely dependent on the growth of vegetation the curve for Columbus, Ohio, whose frostless period begins a little later than at Springfield and Columbia, is given (fig. 1) and compared

[4] H. T. Brown. Fixation of Carbon by Plants. *Nature*, Sept. 14, 1899.

[12] . B. Kincer. Relation between Vegetative and Frostless Periods, MO. WEATHER REV., Feb., 1919, 47: 106.

[13] The unsmoothed values for these curves were obtained as follows: The average of the maximum and minimum temperatures on Apr. 12, 1889, was added to that for Apr. 12, 1890, etc. . . . Apr. 12, 1918, and the total divided by 30. The same was done for all the Apr. 13ths, etc. No attempt was made to smooth the data by harmonic analysis, or by other artificial means to bring out any peculiarities in the curves. It is uncertain how deviations from a smooth harmonic curve should be interpreted. The curves and the discussion may speak for themselves. Even though they can provide no positive *proof* that the cooling effect of vegetative evaporation is responsible for an appreciable part of the temperature depressions cited, the curves, nevertheless, are in accord with what might be expected.—EDITOR.

with Amarillo, Tex. The pronounced change in slope at Columbus appears later, by about the interval anticipated from a consideration of the difference in the frostless period, than at Columbia and Springfield. Both curves show a change in slope, though that for Columbus is the more pronounced. The normal rainfall at Amarillo increases quite rapidly during the latter part of April and the first few days of May and during the month of May has practically the same rainfall as Columbus. The transpiration from the grass and other vegetation in the Amarillo region is considerable during *the time covered by the curves and the slight difference* in the slope for the two stations is therefore not surprising. The record for Amarillo was used because of the scarcity of suitable stations in arid regions that have sufficiently long records.

From theoretical considerations, maximum insolation being received about June 21 and the further rise in temperature resulting from lag (neglecting vegetative evaporation), no pronounced change in the slope of the average daily temperature curve due to the approach to the seasonal maximum would be expected until some time in June, whereas all stations in humid regions that were studied, except for a few mountainous ones with short records, show a pronounced change in slope within 30 days from the date of the last killing frost. The expected change in slope during June is shown in figure 1.

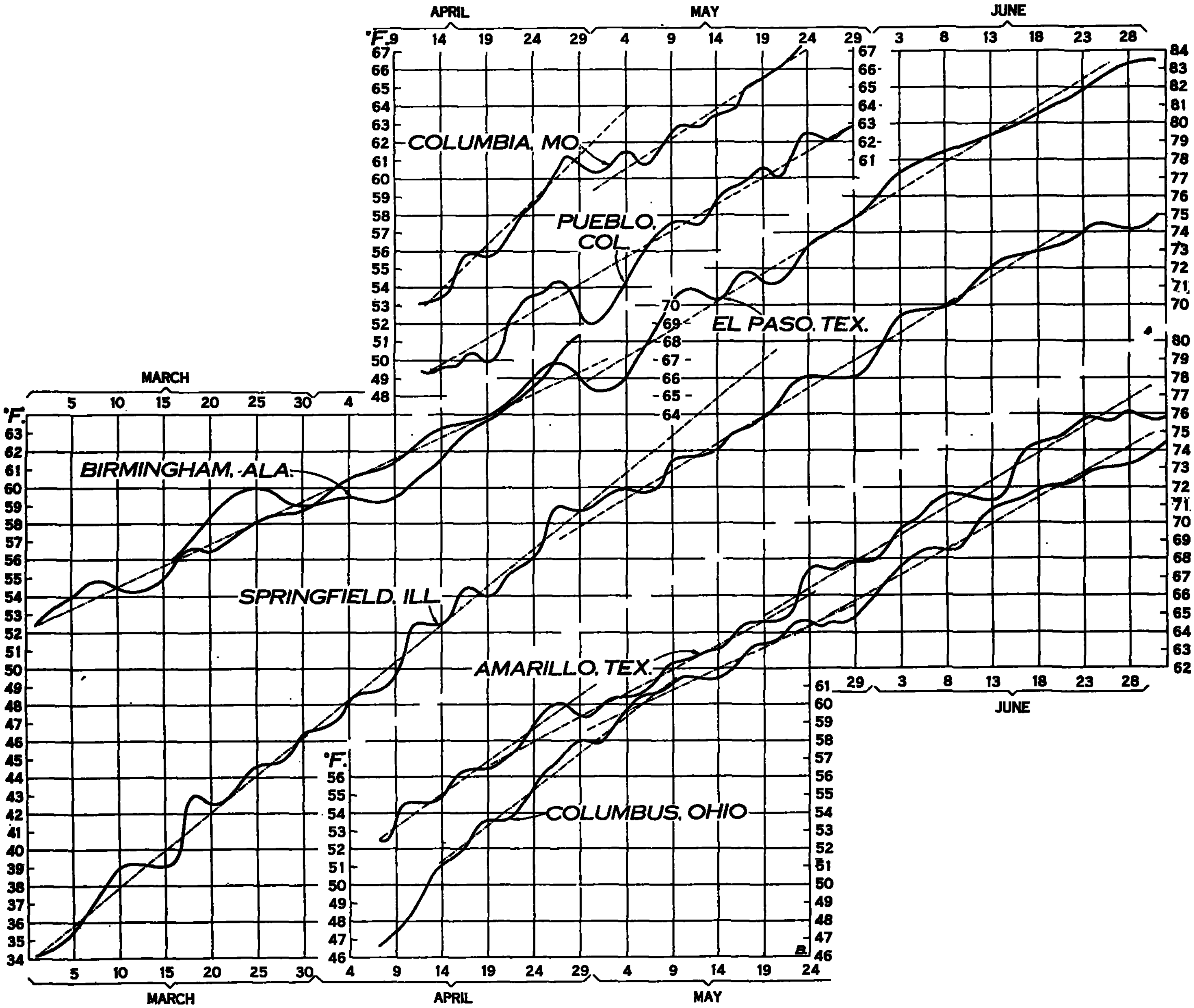

Fig. 1.—Curves of average daily temperature for Columbia, Mo., and Pueblo, Col., for period 1889-1918; for Birmingham, Ala., and El Paso, Tex., based on 23 and 31 years' record, respectively; for Springfield, Ill., and for Columbus, Ohio, and Amarillo, Tex.

Table 1 gives the approximate average date of the last killing frost, the beginning of the vegetative period[14] and the beginning of the noticeable change in the slope *of the mean daily temperature curve for some of the* stations studied that have a record of 20 years or more.

Agreement with the above finding is shown in some of the many temperature curves drawn by van Rijckvorsel,[15]

[14] J. B. Kincer. Relation between Vegetative and Frostless Periods, Mo. Weather Rev., Feb., 1919, 47:106.

[15] E. Van Rijckvorsel. Konstant autretende secundäre Maxima und Minima. First part, 1905.

though the majority of the stations studied by him are not adaptable to this discussion on account of not having typical continental locations.

TABLE 1.

Station.	Approximate average date of last killing frost.	Approximate average date of beginning of vegetative period.	Beginning of noticeable change in slope.
La Crosse, Wis.	May 5	Apr. 11	May 25
Harrisburg, Pa.	Apr. 29	Mar. 23	May 6
Columbus, Ohio	Apr. 30	Mar. 21	May 7
Springfield, Ill.	Apr. 25	Mar. 20	May 1
Columbia, Mo.	Apr. 20	Mar. 19	Apr. 30
Pueblo, Colo.	Apr. 30	Mar. 26	(1)
Lexington, Ky.	Apr. 19	Mar. 12	Apr. 29
Raleigh, N. C.	Apr. 4	Feb. 11	Mar. 25
Amarillo, Tex.	Apr. 23	Mar. 6	Apr. 27
Birmingham, Ala.	Apr. 1	(2)	Mar. 29
El Paso, Tex.	Apr. 1	(2)	(1)

1 No change. 2 Always 43° or above.

Atmospheric circulation in HIGHS and LOWS transport temperatures varying widely from day to day and when marked departures from the average occur with the same sign on the same day for several years the effects of evaporation are obscured. In any event, the evaporative cooling could not be clearly discernible in the records of any single spring. Arid regions on account of less cloudiness receive a greater amount of heat during the day than do humid regions but, on the other hand, they radiate more rapidly at night and, except for the more northern stations where the length of the day during the time involved greatly exceeds that of the night, these differences, presumably, roughly compensate one another. Vegetative evaporation increases the humidity of the air and with all the effects resulting therefrom tends to lessen the variability of temperature in humid regions from day to day. The amount of water thus evaporated at the time of maximum over any area well covered by vegetation is comparable to that from a water surface of the same area. As would be expected, therefore, the curves in humid regions are, as a rule, much smoother than in arid regions.

The distinct flattening so prolonged as that found at some stations was not expected and it may be that other factors were additive to the effect due to vegetative evaporation.[16] The seemingly premature falling off in the rate of temperature increase in humid continental interiors is what was expected would be found, and the evidence (in the light of the known absorption of heat by evaporation) that in such regions it is largely due to vegetative evaporation seems quite conclusive.

[16] For example, an increase in cumulus clouds would delay the rise of the temperature curve in spring.—EDITOR.

NOTE ON EVAPORATION FROM RESERVOIRS.[1]

The report of the committee of the Pacific Coast Electric Light and Power Association appointed for the collection of data on evaporation from reservoirs has recently been submitted. It contains a brief general discussion by the chairman, E. J. Crawford, and is accompanied by papers on the subject of evaporation from reservoirs,[2] by C. H. Lee, C. E. Grunsky, and N. W. Cummings.

In the report of the chairman it is noted that evaporation is apparently less variable than other meteorological phenomena, such as rainfall and temperature, and that the larger portion of the evaporation loss from a reservoir occurs during the summer months.

Mr. Lee concludes that the evaporation from a water surface or from a floating pan is about two-thirds that from a land-exposed buried pan. It is his opinion that for purposes of the hydraulic engineer, floating-pan evaporation observations, if properly made, are the most reliable for reservoir calculations, and a list of precautions which should be observed in obtaining such records is given. These include the following:

The pan should have a surface area of at least 9 square feet and a depth of about 12 inches. It should be fully protected from splash by means of a raft, or otherwise. The water in the pan should be kept clean and at a level approximately the same as that of the surrounding water, and it should be located in deep water and at a sufficient distance from the shore line or other objects to insure normal wind and humidity conditions. Nothing is given as to the effect of the raft in breaking upstream-line flow of the wind, and prevention of the formation of a normal vapor blanket over the floating pan, such as probably exists to some extent at least over the free water surface.

Mr. Grunsky points out, as others have done, that the controlling factor which influences the rate of evaporation from an open body of water is temperature. An empirical formula is given for calculating evaporation in terms of temperature alone. This discussion seems to require the qualification that while the evaporation rate from a given body of water may be expressed fairly accurately, at least as a function of temperature, yet the relation determined for one locality may not, and generally will not, apply with equal accuracy to another location.

Mr. Grunsky points out that in determining the probable loss which will occur from a proposed reservoir through evaporation, present existing data must, in general, be depended upon, since the actual loss can not be measured by pans or other methods until the reservoir is constructed. This observation suggests the importance of further development of methods of correlation of evaporation loss with the factors by which it is controlled, so that it may be possible either to calculate evaporation from existing and widely distributed meteorological data, or so that rational corrections can be made to existing evaporation records so as to render them applicable to a particular location.

Mr. Cummings takes up the problem of determining evaporation losses from a heat balance equation. Theoretically, evaporation loss during a given time-interval can be measured through the amount of heat lost by evaporative processes. If, therefore, the heat supplied to the water during the interval, the gain or loss of heat stored in the water, and the loss of heat through radiation, conduction, or other processes than evaporation, are known, the heat consumed in evaporation and the evaporation itself can be determined. Practically, data for such calculations are almost wholly wanting.

The problem of determining evaporation from a heat balance equation has recently been discussed in a published paper by Ångström, in which such data as are at present available for determination of the various factors in the heat balance equation are presented.[1] It is unnecessary, therefore, to review Mr. Cummings's paper, covering similar ground, at length.—*R. E. H.*

[1] Report of subcommittee of the Pacific Coast Electric Light and Power Association for Collection of Data on Evaporation from Reservoirs, presented at meeting in San Francisco, Feb. 18, 1921.

[2] Already published, or to be published, in the *Journal of Electricity*.

[1] Ångström, Anders: Applications of heat radiation measurements to the problems of the evaporation from lakes and the heat convection at their surfaces. *Geografiska annaler*, 1920, H. 3.